Semiconductor International

Intelligent Microsystems: Strategy for the Future

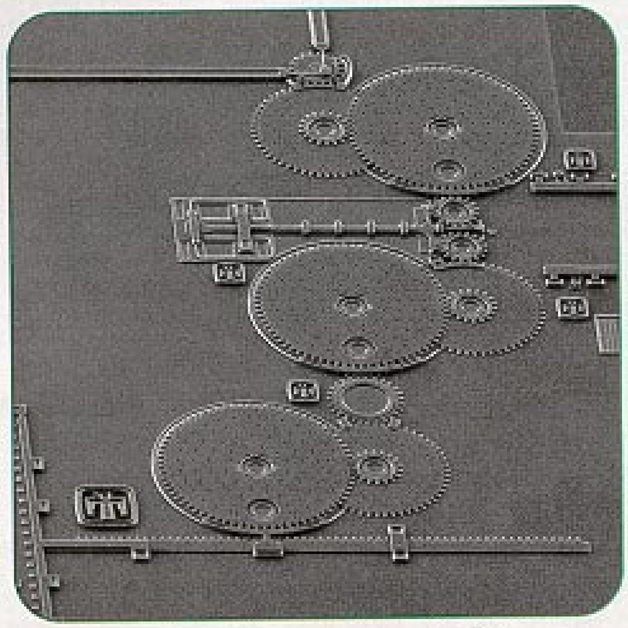
Combining intricate mechanical and electrical functions on one substrate requires special processing.

James H. Smith, Jeffry J. Sniegowski, Paul J. McWhorter, Alton D. Romig Jr.,
Sandia National Laboratories, Albuquerque, N.M.

The next decade will see a revolution in the electronics industry in which the functionality of integrated circuits (ICs) grows beyond the traditional role of processing and storing data and controlling electrical functions. Intelligent microsystems will allow complex systems-on-a-chip to directly interact with their environment by sensing, actuating and communicating without the need for external hardware.

The integration of mechanical functions with electrical functions is required to realize intelligent microsystems. The activity in the area of microelectromechanical systems (MEMS) has, for the most part, concentrated on realizing mechanical functions using semiconductor manufacturing technology. Some success has been made integrating those devices with circuitry on the chip.

One example of a MEMS system is shown in Figure 1. It is a microscopic set of mechanical gears, transmissions, engines, hinges and a linear track made in a conventional IC foundry using conventional semiconductor manufacturing techniques and equipment. MEMS devices are generally sensing elements, or actuating systems like this one.



1. This system contains microscopic mechanical components such as μtransmissions, μengines, μhinges and a linear μtrack. The transmissions shown provide a 12:1 speed reduction and are 250 μm across.

At A Glance . . .

Semiconductor processing technology enables microelectromechanical systems (MEMS) such as sensors and actuators to be realized. Success in combining mechanical systems with CMOS devices promises to make these devices "intelligent." Release and packaging of these devices is the only area where semiconductor processing technology cannot be directly leveraged.

Market drivers

The obvious advantage of an integrated system is size, but the real driver will be cost. Numerous electronic devices such as personal computers and cellular phones have gained cost advantages from integrating most of their functions onto a single chip. The question for MEMS devices is whether integration of mechanical structures with associated electronics can also be accomplished in a cost-effective manner.

The market for microsystems based on semiconductor processing began to emerge in the 1970s with the introduction of the bulk micromachined pressure sensor. Today, these pressure sensors see applications as diverse as in-vivo blood pressure monitoring and automotive manifold air pressure sensing.

Six different market studies for demand of microsystems between 1995 and the year 2000 all show tremendous growth potential.[1] Although the studies differ in their definitions of the microsystem market, cost growth models and groups surveyed (suppliers vs. end-users), they all project growth potential ranging from $3 billion to 30 billion by the year 2000.

2. *A focused ion beam cross section of a set of coupled gears built in Sandia's SUMMiT-V process.*

Technology leverage

Although there are a variety of technologies that fall under the umbrella of microsystems, the vast majority depends on lithography and etching from the semiconductor industry. Some technologies, such as polysilicon surface micromachining and integration of mechanics with electronics, draw their techniques almost entirely from semiconductor processing. Other techniques such as LIGA (a German acronym for lithography, electroforming and injection molding) leverage only lithography from the semiconductor world.

Some commercial devices, such as the ADXL series of accelerometers from Analog Devices (ADI) and the Digital Micromirror Device from Texas Instruments (TI), draw their manufacturing techniques almost entirely from the semiconductor area. The primary goal in producing commercial devices like these is not to manufacture small integrated devices, but to manufacture inexpensive, small integrated devices.

ADI's accelerometers are an example of a manufacturing technology that produces sophisticated sensing devices that are competitive in the highly cost-conscience automotive industry. Though scaling to full production taxes a production line such as ADI's, the MEMS devices have been successful enough for ADI to pursue next-generation devices, licensing a modular integration process developed at Sandia National Laboratories.

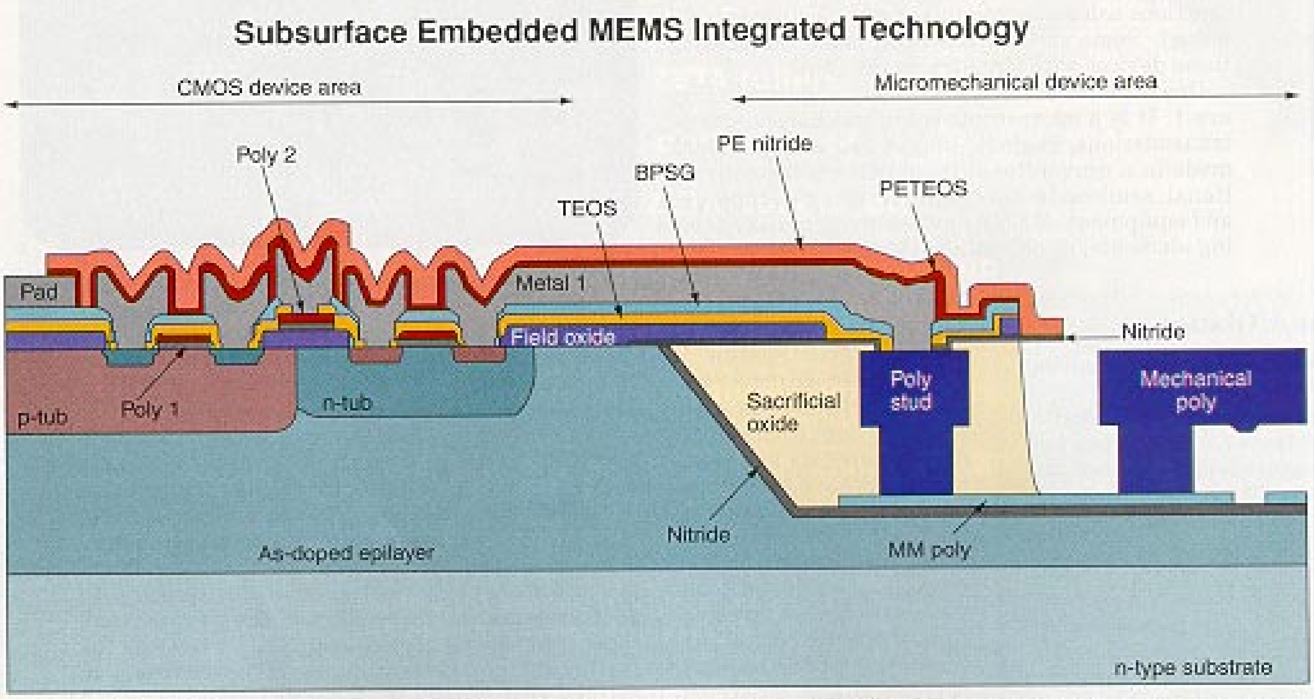
Reliability

Although cost may be a dominant driver, reliability is of prime concern and is closely related to the manufacturing process. The semiconductor industry has demonstrated that integration onto a single chip significantly improves reliability. A monolithically integrated MEMS/CMOS product, TI's DMD, exemplifies this second important trait of semiconductor manufacturing. For DMD display application, a few or even one pixel of several million can easily be discerned by the human eye. Therefore, near-perfect performance of all the mirrors for the lifetime of the product is necessary.

As the sophistication of mechanical components being built in MEMS technologies increases, a need for additional design flexibility and an increased number of structural layers is generated. Sandia has developed a five-layer polysilicon surface micromachining process (SUMMiT-V) to address this need. A focused ion beam (FIB) cross section of two coupled gears on a moving plate built in the SUMMiT-V process is shown in Figure 2. A wider view of the device that uses those gears along with other mechanical components is shown in Figure 1. For reference, the transmissions shown in this figure provide a 12:1 speed reduction and are 250 µm across.

Integrating MEMS and CMOS

The integration of mechanical and electrical functions presents some



3. *An embedded micromechanics approach builds MEMS devices in trenches first, buries them for CMOS device processing and then releases them to produce the final system.*

interesting challenges. A recent review paper[2] noted that micromechanical structures require long, high-temperature anneals to ensure complete relaxation of stress. CMOS technology requires very planar surfaces to successfully perform the necessary lithography. If the micromechanical steps are performed first, substrate planarity is sacrificed. If the CMOS is built first, it must withstand high-temperature anneals.

One approach is to perform the CMOS fabrication first, using tungsten instead of aluminum for interconnection. The tungsten can withstand the subsequent anneals, but issues of adhesion and silicide formation have yet to be answered.[3] Another approach is a micromechanics-first method developed at Sandia.[4] The micromechanical devices are fabricated in a trench etched on the surface of the wafer (Fig. 3). After the devices are finished, the trench is filled with oxide, planarized using chemical-mechanical polishing (CMP) and sealed with a nitride membrane. Conventional CMOS processing is then performed. Additional steps are performed at the end to expose and release the micromechanical devices.

Table 1. Comparison of Typical IC and MEMS Device Characteristics

	ICs	MEMS
Film thickness (μm)	<1	2-6
Critical dimension (μm)	0.35	1
Aspect ratio	2:1	6:1
Topography (μm)	<1	4-10
Device size (μm)	1	100

Adapting to microsystem manufacture

For semiconductor equipment and material suppliers to adapt to the needs of microsystem manufacturing, their main differences must be addressed. Microsystem manufacturing requires greater film thicknesses, aspect ratios and topography (Table 1). MEMS film thicknesses, etch aspect ratios and the resulting topography are all greater than those currently found in IC manufacturing. The overall dimension of a MEMS component can be 100 μm or larger, compared to the ~1 μm linear dimension of today's microelectronic devices.

The film thickness of MEMS and the resulting topography generate special needs for manufacturing equipment in the areas of film deposition, lithography, etching and planarization. Deposition equipment and processes must be able to accommodate the increased film thicknesses without excessive downtime for maintenance and cleaning. A single MEMS deposition can be equivalent to 10 depositions for an IC process in terms of maintenance requirements.

These thicker films must also be relatively low in stress and stress gradient to prevent film delamination, film cracking, dimensional changes and curling of the final MEMS structures. The IC industry is very good at monitoring film properties of importance to the electrical performance of completed circuits, but manufacturing processes used for MEMS require the monitoring of mechanical properties as well.

Step coverage is an issue, as well as keyhole formation during the fill of high-aspect ratio trenches. MEMS present special challenges for lithography in terms of depth of focus, control of the focal plane and photoresist coating and removal. Wafer bow induced from the stresses of the thicker films used for MEMS can create lithography problems, as well as problems with robotic wafer handling equipment.

Dry etching equipment and process for MEMS fabrication must deliver increased mask and stopping layer selectivity, increased etch rates and high-aspect ratio trenches. The elimination of stringers near topographical features is also an important consideration for etching equipment. The use of planarization techniques such as CMP, spin-on-glass, depostion/etch-back processes and double local oxidation of silicon (LOCOS) can help eliminate many of the topographical requirements of MEMS, along with a relaxation of processing equipment requirements. CMP has proved to be particularly effective at increasing the manufacturability of MEMS devices in conventional IC processing equipment.

Release and packaging

The final area of equipment development for MEMS devices is in the release and packaging of the MEMS components. The last step in most MEMS manufacturing processes is the removal of a sacrificial film, usually oxide or photoresist, to free the moving mechanical structures. Equipment for this removal and the subsequent handling of the released MEMS structures have unique requirements. Several techniques at the "laboratory" level have been investigated and will provide potential equipment markets for vendors.

The issues related to release and packaging may be the largest commercial barrier to new MEMS products. The tool set and processes used in the manufacturing of MEMS are closely matched to IC manufacturing, but the release and packaging techniques are not able to achieve this same high degree of leverage. Commercial successes of monolithically integrated MEMS devices to date have been able to leverage packaging techniques for conventional ICs or optical devices to some extent, but have required extensive modification.

Summary

The rapidly growing field of microsystems in general and in MEMS specifically offers significant advantages over conventional products in the areas of cost, volume, weight and reliability. Existing equipment and processes for deposition, lithography, etching and planarization can be leveraged to meet the needs of this rapidly emerging field. Entirely new equipment and techniques, though, are required for the release and packaging of MEMS components. Further information about microsystems, MEMS and links to other MEMS research program web pages can be found at Sandia's Micromachine web site at www.mdl.sandia.gov/Micromachine. □

Acknowledgments

This work was supported by the U.S. Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corp., a Lockheed Martin Company, for the U.S. Department of Energy.

References

1. S. Marshall, "MEMS market data: Another case of sorry — wrong number?" Micromachined devices, 1997, p. 6.

2. R. Howe, "Polysilicon integrated microsystems: technologies and applications," *Proc. Transducers '95*, pp. 43-46, (1995).

3. J.H. Smith, S. Montague and J.J. Sniegowski, "Material and processing issues for the monolithic integration of microelectronics with surface machined polysilicon sensors and actuators," *Micromachining and Microfabrication '95*, SPIE.
4. J. Smith, S. Montague, J. Sniegowski, J. Murray and P. McWhorter, "Embedded micromechanical devices for the monolithic integration of MEMS with CMOS," *Proc. IEDM '95*, pp. 609-612, (1995).

James H. Smith, Ph.D., P.E. has been developing polysilicon surface micromachining technologies and devices at Sandia's Microelectronics Development Laboratory since 1992. He is the manager of the Intelligent Micromachine Department.
Phone: (505) 844-3098
Fax: (505) 844-2991
E-mail: smithjh@sandia.gov

Jeffry J. Sniegowski, Ph.D. is a principal member of the technical staff in the Intelligent Micromachine Department at Sandia National Laboratories. He has been the technical lead in the development of micromachining technologies and micromachined actuators for the Intelligent Micromachine Department for the past seven years.
Phone: (505) 844-2718
Fax: (505) 844-2991
E-mail: sniegojj@sandia.gov

Paul J. McWhorter joined Sandia's Reliability Physics Department in 1985 and initiated Sandia's Intelligent Micromachine Initiative in 1992. He is presently serving as deputy director for Sandia's Microelectronics and Photonics Center.
Phone: (505) 844-4683
Fax: (505) 844-7833
E-mail: mcwhorpj@sandia.gov

Dr. Alton D. Romig Jr. has been the director of the Microelectronics and Photonics Center at Sandia since 1995. In addition to his responsibilities at Sandia, he is also president of ASM.
Phone: (505) 844-8358
Fax: (505) 844-2423
E-mail: adromig@sandia.gov

Reader Interest Review

Please help our editors evaluate your interest in this article. Circle the number indicated on the Reader Service Card.

High 179 Medium 180 Low 181